

Cosmological neutrino mass detection: The best probe of neutrino lifetime

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Future cosmological data may be sensitive to the effects of a finite sum of neutrino masses even as small as ~ 0.06 eV, the lower limit guaranteed by neutrino oscillation experiments. We show that a cosmological detection of neutrino mass at that level would improve by many orders of magnitude the existing limits on neutrino lifetime, and as a consequence on neutrino secret interactions with (quasi-)massless particles as in majoron models. On the other hand, neutrino decay may provide a way-out to explain a discrepancy $\lesssim 0.1$ eV between cosmic neutrino bounds and Lab data.

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Introduction Recent years have seen an impressive improvement on the cosmological constraints to the sum of neutrino masses $\Sigma = \sum m_\nu$ (for reviews see [1, 2]), with current limits typically ranging below 1 eV, and the most aggressive bounds (but also the most fragile ones with respect to unaccounted systematics) already at $\Sigma \lesssim 0.2$ eV, 95% C.L. [3, 4]. Several forecast analyses suggest that cosmological probes will reach in the future an incredible sensitivity to the effects of even a tiny mass of the cosmic background neutrinos. In particular, cosmic microwave background (CMB) lensing extraction may be sensitive to $\Sigma \simeq 0.035$ eV [5]; CMB plus weak galaxy lensing with tomography may also push the sensitivity to Σ below the level of ~ 0.05 eV [6, 7], with an error as low as ~ 0.013 eV [6]. Also galaxy cluster surveys may probe Σ down to ~ 0.03 eV [8], and a sensitivity down to 0.05 ± 0.015 eV may be reached combining CMB with the data from the Square Kilometre Array survey of large scale structures [9]. These forecasts show that cosmology has a potential sensitivity to neutrino masses well below the 0.1 eV level. Of course, the ultimate level of the systematics to beat has yet to be reliably established. On the other hand, the synergy between different strategies and probes may help to identify the systematics, and also to improve over the above-mentioned figures of merit.

The interest of these expectations relies on the fact that neutrino oscillation data imply $\Sigma \gtrsim 0.06$ eV, where the minimum $\Sigma \simeq 0.061 \pm 0.004$ eV is attained for a normal hierarchy (NH; values quoted at 2σ , see [4]). For the case of an inverted mass hierarchy (IH), the oscillation data imply $\Sigma \simeq 0.1$ eV. In the following, we shall proceed under the assumption that cosmological observations will be able to probe these Lab predictions. To be defined, we shall assume that neutrinos have a hierarchical spectrum of either inverted or normal sign, as favored by many theoretical models, including the simplest seesaw ones. A degenerate mass scenario is phenomenologically allowed, with the existing constraints given by $\Sigma < 6 - 7$ eV if only laboratory bounds from tritium endpoint [10] are used, or $\Sigma < 0.2 - 2.0$ eV from existing cosmological observations, where the range depends on the datasets and priors

assumed [1, 2]. The degenerate scenario can be tested to some extent independently from cosmological observations via future tritium endpoint spectrum [11] and (if neutrinos are majorana particles) neutrinoless double beta decay [12] experiments. We want to remark, however, that our considerations would apply qualitatively to a mildly degenerate mass pattern, too.

The main point of this paper is to motivate that, if a positive cosmological mass detection is achieved as expected, one will be able to put a remarkably strong constraint on the neutrino lifetime. Note that previous attention has been paid to the cosmological signatures of decaying neutrinos [13]. Yet the mass range explored in those papers is very large compared to present bounds, and the main signature considered was the impact on the integrated Sachs-Wolfe effect on the CMB. In our considerations, the bound comes from the impact that massive neutrinos have in the background evolution of the universe, in a range of masses where they are relativistic well after the CMB decoupling.

Bounds on neutrino lifetimes are usually quoted in terms of the rest-frame lifetime to mass ratio τ/m . Given a measurement in the time interval t using neutrinos with Lab energy E , the naive bound which one can put is $\tau/m \gtrsim t/E$. Using then the longest timescale available, the universe lifetime $t_0 \simeq H_0^{-1}$ (where H_0 is the Hubble constant), and the lowest energy neutrinos, the ones of the cosmic background which are at least partially non-relativistic, a bound of the order of $(m_{50} \equiv m/50 \text{ meV})$

$$\frac{\tau}{m} \gtrsim \frac{1}{m H_0} \simeq 10^{19} m_{50}^{-1} \text{ s/eV}, \quad (1)$$

is the strongest constraint attainable in principle. This is to be compared with the strongest direct bound available at present given by the observation of solar MeV neutrinos, of the order of $\sim 10^{-4}$ s/eV [14], and the much stronger (but model dependent) bound $\tau/m \gtrsim 10^{11}$ s/eV, which might derive from the observations of diffuse supernova neutrino background [15]. Recently, a bound comparable to those projections, $\tau/m \gtrsim 4 \times 10^{11} m_{50}^2 \text{ s/eV}$, has been claimed to follow already from the requirement that the neutrinos are free-streaming at the time of the

photon decoupling, as deduced by precise measurements of the CMB acoustic peaks [16]. Yet, the robustness of this conclusion has been questioned in [17]. We shall see that the proposed bound based on cosmological neutrino mass detection would be much closer to the maximal theoretical bound of Eq. (1), thus superseding by several orders of magnitude the previous ones. More importantly, it is not based on a model for secret neutrino interactions, but on the “observation” of neutrino survival, and it applies whatever the final state light particles are.

The bound In order to estimate the bound on the neutrino lifetime from the cosmological observation of the neutrino mass, let us recall first how massive neutrinos affect cosmological observables. We shall base the following discussion mostly on the treatment given in [1], which we address for details and further references. The main effect is due to the direct or indirect impact of massive neutrinos in the background evolution (Friedmann law) of the universe. In particular, in the matter epoch (but the extension to a late dark energy dominated phase is straightforward [1]) and assuming stable neutrinos the Friedmann equation writes

$$\frac{1}{a^2} \left(\frac{\dot{a}}{a} \right)^2 = \frac{8\pi G_N}{3} (\rho_m + \rho_\nu) \simeq \frac{8\pi G_N}{3} \rho_m (1 + f_\nu), \quad (2)$$

where a dot represents a derivative with respect to the conformal time η , a is the scale factor of the universe, G_N is Newton’s constant, ρ_m is the average cold dark matter (CDM) plus baryon density, and ρ_ν is the neutrino energy density; we have defined $f_\nu \equiv \rho_\nu / (\rho_m + \rho_\nu)$ and the second equality in Eq. (2) holds to first order in f_ν . Keeping e.g. $\rho_m + \rho_\nu$ constant, a non-vanishing f_ν today would change the epoch of matter radiation equality a_{eq} with respect to the massless neutrino case, with a scaling $a_{\text{eq}} \propto (1 - f_\nu)^{-1}$ (assuming ultrarelativistic neutrinos at the time of equality). This is responsible for the main effects on the CMB anisotropy pattern, in the range $\Sigma \lesssim 2.0$ eV. Physically, postponing the time of equality produces an enhancement of small-scale perturbations, especially near the first acoustic peak, and increases slightly the size of the sound horizon at recombination. When turning to the growth of structures, there is also an additional effect. During matter domination and on scales smaller than the free-streaming scale, the neutrino perturbations do not contribute to gravitational clustering, and neutrinos can be simply omitted from the Poisson equation. On the other hand, they do contribute to the homogeneous expansion through Friedmann equation. Therefore the exact compensation between clustering and expansion holding for a pure CDM scenario is slightly shifted: the balance is displaced in favor of the expansion effect, and the gravitational potential decays slowly, while the matter perturbation does not grow as fast as the scale factor. Combining the continuity, the Euler, the Poisson and the Friedmann equations one gets

the evolution law for the perturbation in the matter density field δ_m at small-scales [1],

$$\ddot{\delta}_m + \frac{2}{\eta} \dot{\delta}_m - \frac{6}{\eta^2} (1 - f_\nu) \delta_m = 0, \quad (3)$$

which at the first order in the small parameter f_ν has a growing mode solution of the kind $\delta_m \propto a^{1-\frac{3}{2}f_\nu}$. This is valid when ρ_ν is dominated by the most massive, non-relativistic state(s), and $f_\nu \rightarrow \text{constant}$. Physically, the combined effect of the shift in the time of equality and of the reduced CDM fluctuation growth during matter domination produces an attenuation of perturbations for modes $k > k_{\text{nr}}$, where k_{nr} is the minimum of the comoving free-streaming wavenumber attained when neutrinos turn non-relativistic, and given by [1]

$$k_{\text{nr}} \simeq 1.5 \times 10^{-3} m_{50}^{1/2} \text{ Mpc}^{-1}. \quad (4)$$

An instantaneous decay of the massive neutrinos at an epoch η_d in the matter era can be thought as replacing the neutrino fluid with one having the same energy content at η_d , but whose energy density scales from that moment on as a^{-4} , since the daughter particles are relativistic. Let us estimate how large a value of η_d , or equivalently of the proper time $t_d (= \tau$ if the neutrino is non-relativistic), can be probed cosmologically. Quickly after the neutrino decay one has formally $f_\nu \rightarrow 0$, provided that $t_d \ll t_0 \simeq H_0^{-1}$; from that moment on, the cosmological effects of the decaying neutrino scenario are analogous to the ones of a massless neutrino universe. The condition $t_d \ll t_0$ is required by the fact that when $t_d \rightarrow t_0$, the radiation content of the relativistic daughters of the massive neutrino has no time to decline to zero with respect to the matter density. This condition is necessary to change appreciably the energy budget of the universe, thus affecting the predicted growth of the structures and the time of equality with respect to a massive neutrino scenario. Clearly, for a given sensitivity to the effect of neutrino masses there is a maximum value t_d^{max} which would result in a detectable change of cosmological observables. A precise estimate of this parameter would imply a detailed forecast analysis, which goes beyond the purpose of this paper. Yet, a simple argument shows that, relying on the existing forecasts, a conservative lower limit is $t_d^{\text{max}} \gtrsim t_{\text{nr}}$, where t_{nr} is the epoch at which the heavier neutrinos become non-relativistic, whose redshift is defined by $m = 3 T_{\nu,0} (1 + z_{\text{nr}})$, $T_{\nu,0}$ being the present temperature of the neutrino gas. Indeed, when the decay epoch satisfies $t_d \lesssim t_{\text{nr}}$, the energy content of the products is the same of a relativistic neutrino fluid, and it redshifts the same way. So, all physical effects of this scenario are basically the same of the case where neutrinos are massless¹. In Fig. 1, from top to

¹ Cosmological probes other than big bang nucleosynthesis (BBN)

bottom as seen from the left side of the plot, we show $f_\nu(z)$ for the following cases: (i) a massive neutrino cosmology, where we assume an IH neutrino mass pattern and the lightest neutrino is massless; (ii) as in (i), but for NH; (iii) a decaying neutrino cosmology, where massive neutrinos have IH; (iv) as in (iii), but for NH; (v) a massless neutrino cosmology. For the decaying cases, we assume that all massive neutrinos decay at $t_d = t_{\text{nr}}$, where t_{nr} is the time of non-relativistic transition of the heaviest neutrino state ($m \simeq 0.05 \text{ eV}$). The neutrino mass and mixing parameters are from [4], the cosmic neutrino distributions are from [18], and for simplicity we have assumed a matter-dominated cosmology with the matter density parameter $\Omega_m = 0.24$ and the reduced Hubble constant $h = 0.73$ [19].

Clearly, the cases (iii), (iv), and (v) are very similar (exactly degenerate if $t_d \ll t_{\text{nr}}$) and, as long as $t_d \lesssim t_{\text{nr}}$, if the massless neutrino case can be disproved, the decaying neutrino bound immediately follows. The improvement in the bound on the neutrino lifetime is tremendous. In particular, neutrinos turn non-relativistic at $z_{\text{nr}} \simeq m/3T_{\nu,0} \simeq 100 m_{50}$, i.e. when the universe has about $(100 m_{50})^{-3/2} \sim 10^{-3} m_{50}^{-3/2}$ of its present age, and the bound is about $10^{-3} m_{50}^{-3/2}$ of the maximum attainable limit reported in Eq. (1),

$$\frac{\tau}{m} \gtrsim 10^{16} m_{50}^{-5/2} \text{ s/eV}. \quad (5)$$

Obviously, the previous argument does not exclude that an accurate forecast analysis may reveal a sensitivity to a somewhat larger t_d^{max} . Note also that we do not require that cosmological data need to distinguish between NH and IH: if future observations will suggest e.g. $\Sigma = 0.08 \text{ eV}$ with a 1σ error of 0.02 eV , the two neutrino mass patterns would be both consistent within 1σ with the best fit, yet a complete decay of neutrinos into relativistic particles with lifetime lower than the value reported in Eq. (5) could be excluded at 4σ . Of course, for a given cosmological sensitivity, the significance of the above bound increases if the inverted hierarchy is realized in nature: in that case $\Sigma \simeq 0.1 \text{ eV}$ holds, and the cosmological effects of neutrino masses are larger. Note that accelerator neutrino experiments [20], magnetized detectors of atmospheric neutrinos [21], direct mass searches [22], and the serendipitous observation of neutrinos from a galactic supernova [23] may all be used to determine the mass hierarchy. It is thus possible that by the time

are basically insensitive to the energy spectrum of the neutrino fluid: They are only sensitive to its overall energy density and equation of state. In the case at hand, one or more of the daughter particles may have a finite but much smaller mass than the parent one, but this does not change our conclusions, at least at our level of approximation.

cosmology will be sensitive to $\Sigma \lesssim 0.1 \text{ eV}$, the hierarchy information may be available independently.

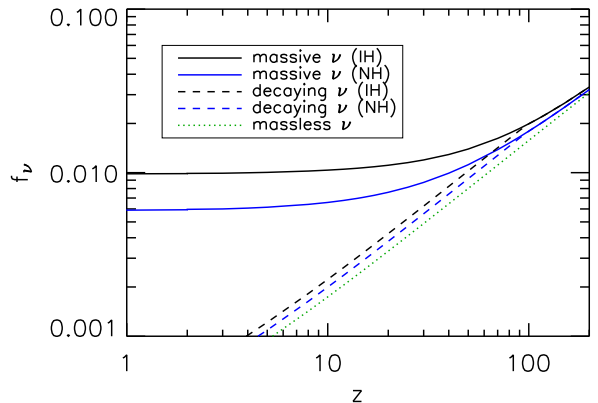


FIG. 1: The function $f_\nu(z)$ for the relevant cosmological cases considered in the text.

To appreciate how strong the bound of Eq. (5) would be, let us consider a model of a “secret” neutrino interaction with a (quasi-)massless majoron field ϕ of the kind $\mathcal{L} = g \bar{\nu}_i \nu_j \phi + \text{h.c.}$, i, j labeling different mass eigenstates. The total decay rate for a hierarchical neutrino mass pattern and summing over neutrino and antineutrino final state channels is [14, 16]

$$\Gamma_d = t_d^{-1} = \frac{g^2}{16\pi} m. \quad (6)$$

This holds in the neutrino rest frame, but in our case this is also the Lab decay width, give or take a factor $\mathcal{O}(1)$, since the neutrino is just turning non-relativistic. The constraint of Eq. (5) leads to the stringent bound

$$g \lesssim 4 \times 10^{-14} m_{50}^{1/4}. \quad (7)$$

This has to be compared with traditional bounds found in the literature in the range $g \lesssim 10^{-4} \div 10^{-5}$ (see e.g. [24]), which is also a typical value invoked in the “neutrinoless universe” scenario of Ref. [25]. Even the extremely stringent bound reported in [16] is more than two orders of magnitude weaker.

Note that the tiny couplings which may induce the decay are not sufficient to thermalize extra degrees of freedom in the early universe. So, this model does not predict departure from the standard expectation for the effective number of neutrinos N_{eff} [18], which can be consistently fixed in deriving the bound. Yet, if additional exotic physics is present, a change (typically an increase) of N_{eff} is possible. The effect of a finite Σ can be partially compensated by an increase in N_{eff} , which worsens the sensitivity of cosmological probes to Σ (see e.g. [26]). However, the inclusion of these exotic effects in the

forecasts can safely follow the standard parameterization used in analyses of stable neutrino scenarios.

Discussion and conclusion Current forecast analyses suggest that future cosmological surveys may attain the sensitivity to detect the effects of a sum of neutrino masses as small as ~ 0.06 eV, the lower limit predicted by oscillation data. Provided that the systematics can be controlled to that level, we have discussed in this paper how such a detection would have profound consequences for the particle physics of the neutrino sector, besides providing a way to measure the absolute neutrino mass scale. In particular, when taking into account the expectations from the Lab, excluding the $\Sigma = 0$ case would improve by many orders of magnitude the existing limits on neutrino lifetime, and as a consequence on neutrino secret interactions with (quasi-)massless particles as in majoron models. Strictly speaking these bounds apply to the heaviest (or the two heaviest, in IH) mass eigenstate, but naturalness and phase-space considerations suggest that the lifetime of the lightest state(s) is longer, and its coupling with a majoron field weaker, than for the heavier one(s). Also, such a bound would be robust with respect to the coupling mediating the new interaction (the same may not apply to the considerations of [16], for example). It also applies to any possible invisible decay channel, provided that the total mass of the final state particles is much smaller than Σ . In particular, this bound applies to 3ν final state decays $\nu_i \rightarrow \bar{\nu}_j \nu_k$, as well as to decays $\nu_i \rightarrow \nu_j + \phi$ in majoron-like models. As discussed in [16], a consequence of such stringent bounds is that the decay of high energy neutrinos [28], a target for neutrino telescopes such as IceCube, can not occur. Here the conclusion would extend to the diffuse supernova neutrino background, too: a disagreement with astrophysical predictions could not be attributed to neutrino decays. We think that the idea developed here provides a beautiful example of interplay between particle physics, cosmological and astrophysical arguments and motivates further the efforts to fully exploit the potential of future cosmological surveys.

Finally, it is worth speculating briefly on the possibility that, although future observations may attain the needed sensitivity, a value of Σ consistent with zero is favored². This paper suggests that a neutrino lifetime $\tau \lesssim t_{\text{nr}}$, as may be due to an extremely tiny coupling of the order of $g \gtrsim 4 \times 10^{-14}$ with a majoron-like particle, might provide a possible explanation of a discrepancy with oscillation and Lab data, at least if this should arise at the $\Sigma \lesssim 0.1$ eV level (thus insufficient e.g. to fully ex-

plain the tension between cosmological mass bounds and the claim of detection of neutrinoless double beta decay [27]). Note that this possibility has some similarity with the “neutrinoless universe” scenario of Ref. [25], since it offers a way-out for a possible non-detection of neutrino mass in cosmological data, thus re-emphasizing the complementarity of cosmological bounds and laboratory experiments. However, differently from the latter, it would present no departure from the standard cosmology as early as the BBN or CMB photon decoupling epoch. This avoids completely the constraints based e.g. on N_{eff} discussed in [25] as well as the more stringent arguments put forward in [16].

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² Note that the accuracy needed to detect a finite Σ (thus improving the bound on the neutrino lifetime) in general differs from the accuracy with which $\Sigma \simeq 0$ can be favored: disproving neutrino decay may be less challenging than the opposite.

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